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Predicting Spontaneous Combustion in Spoil Piles from Open cut Coal Mines

J N Carres¹ and A Saghafi¹

SUMMARY

Spoil piles are produced routinely in open cut coal mines. Spoil piles may contain waste coal and other carbonaceous horizons. Coal and carbonaceous materials react with oxygen in the atmosphere, producing heat. If the rate at which heat is generated is greater than the rate at which heat can be dissipated, the temperature of the spoil pile rises. If the heating remains unchecked, spontaneous combustion can occur. Spontaneous combustion poses significant safety, environmental and economic problems if it should become established in spoil piles. Using the basic features of self heating in spoil, the use of model is directed toward developing quantitative prediction of spontaneous combustion in open cut coal mine spoil piles.

INTRODUCTION

Self heating leading to spontaneous combustion is a moderately common occurrence in coal mining. Many mines have experience with the phenomenon. This can range from the nuisance value of small outbreaks in waste coal through to threats to the safety of mine personnel from spontaneous combustion in underground coal mines. Indeed sometimes in underground coal mines, spontaneous combustion has had disastrous consequences. Similarly in the transportation of coal, great care must be given to the likelihood of heating as fires aboard ships or barges can also prove to be disastrous. In open cut coal mining, the major emphasis has been on the environmental consequences of spontaneous combustion in spoil piles. Safety issues, however, also present themselves as combustion may erode large volumes of spoil at depth leading to subsidence, with or without added surface loads from people or vehicles (Kim and Chaiken, 1993).

While the main cause of spontaneous combustion is the exothermic reaction of coal with oxygen in the atmosphere and while many factors are known to affect the likelihood of spontaneous combustion (such as prevailing winds, cover layers, particle size distribution, amount of reactive material in the spoil) there is to date, no general method which allows quantitative predictions of spontaneous combustion. The work presented in this paper is aimed toward developing quantitative methods which will be able to improve markedly the ability to predict spontaneous combustion.

SPOIL PILES

Spoil piles are associated with open cut coal mining and are a necessary part of the mining process. Large quantities of material, removed to uncover the seam (or seams) to be mined are dumped to form spoil piles which, in general, are made up of broken sedimentary rocks including sandstone, mudstone, siltstone and carbonaceous shales. In addition thin coal seams, which are uneconomic to mine, as well as partings material which can contain appreciable amounts of carbonaceous material can also be dumped. Fig.1 illustrates an idealised dragline spoil pile and shows a row of individual dragline dumps. The valleys between the spoil piles are often in-filled with carbonaceous material associated with the coal seams.

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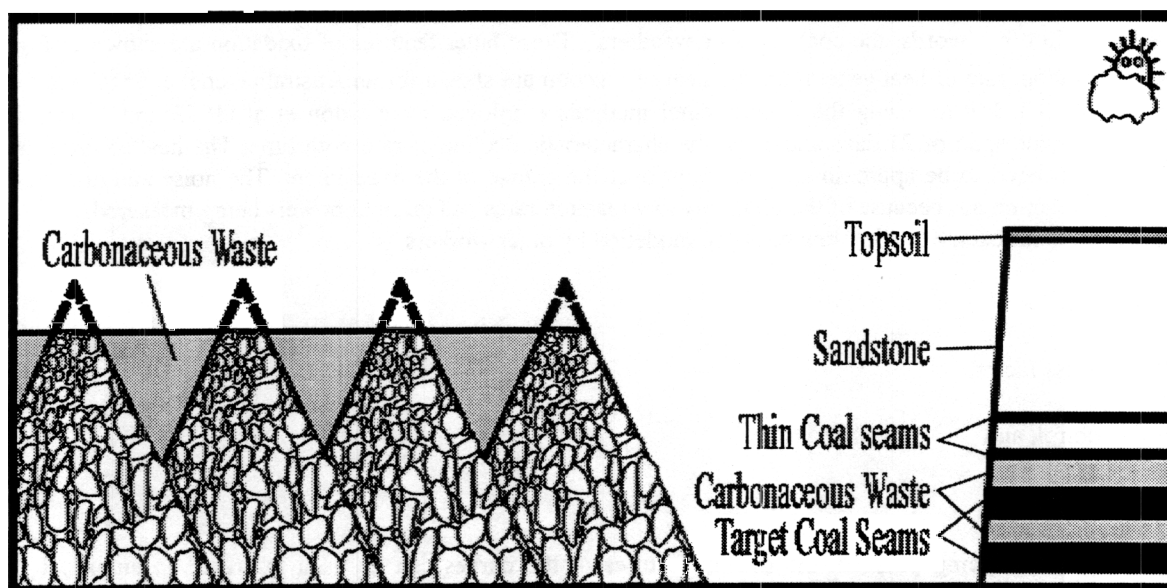


Fig. 1 - Schematics of a dragline tipped spoil pile

Spoil piles are complex structures as they consist of a mixture of materials with differing reactivities to oxygen as well as a broad particle size distribution (Carras et al, 1994). In addition the material distribution in spoil piles depends on the nature of the strata before mining, as well as the method of mining and dumping with each mining method resulting in a different overall layering or mixing of the materials. For instance, a dragline will give rise to a different sequence of layers to a shovel with truck tipping over a face. Segregation of particle sizes also occurs as material rills down the spoil slope. In broad terms spoil piles may be pictured as structures of reactive material which allow the transport of gases and heat, with the gases of main concern in the initiation of self heating being oxygen and water vapour.

SELF HEATING

Self heating results when the rate at which heat is generated within a structure is greater than the rate at which the heat can be lost to the environment. In order to provide quantitative descriptions of self heating it is necessary to quantify the heat generation and loss processes. In spoil piles there are four major sources of heat. The most important is the direct oxidation of coal. Oxidation of other carbonaceous strata (eg shales, siltstones and mudstones) also occurs. The third source is the oxidation of reactive pyrite, commonly associated with coal seams. In addition condensation of water vapour within a porous structure (due to changes in relative humidity) can release considerable heat and aid self heating.

Sources of heat

1. Coal oxidation

The exothermic interaction of coal with oxygen has been studied for many years (Carras et al, 1994; Nordon, Young and Bainbridge, 1979; Nelson, 1989; Krishnaswamy et al, 1996; Chen and Stott, 1997; Khan, Everitt and Lui, 1990). While there is continuing debate as to the details of the reactions and the relative importance of different mechanisms, at $\sim 35^{\circ}\text{C}$ the rate of initial oxidation for coals is ~ 0.1 to $\sim 8 \times 10^9$ ($\text{g O}_2/\text{g coal/s}$), for a particle size range of $-3.3+1.7\text{mm}$, depending on the coal being considered (Carras and Young, 1994). Further, measurements based on isothermal calorimetry (Nordon et al, 1985) have shown values of the heat of reaction of ~ 250 to 400 kJ/mol O_2 . Such rates of reaction and heat generation give rise to thermal outputs of $\sim 10^6$ to 10^4 W/g coal for coal oxidising without oxygen limitation at $\sim 35^{\circ}\text{C}$.

The rate of reaction has also been shown to depend, inter alia, on temperature, particle size, oxygen partial pressure, water content and extent of previous oxidation. The rate of reaction increases with temperature, Arrhenius fashion, but decreases with time of reaction. In other words, the coal ‘ages or weathers’. These latter features of oxidation are shown in Fig. 2 where the rate of oxidation, rate of heat generation and heat of reaction are shown for an Australian coal at 55°C and for a particle size range of -3.3+1.7mm using the experimental methods employed by Nordon et al (1979 and 1985). The measurements cover a time span of 21 days and show the characteristic decline of rate with time. The heat of reaction is also shown and is considered to be approximately constant over the course of the experiment. The noise and drift in the values for the heat of reaction are because of the relatively low reaction rates and thermal powers being measured. The origin of the decline in reactivity with time has been modelled by other workers as

1. shrinking core
2. an effectiveness factor
3. diffusion control, and
4. an Elovich process.

While these details are still being pursued, the overall features of the curves can be used to create an empirical rate equation for coal where the rate of heat generation can be written

$$Q = H_o R_o = H_o A f(r) C^n \exp(-E / RT) \exp(-\alpha q)$$

where Q is the rate of heat generated per unit mass of coal, H_o is the heat of reaction, R_o is the rate of reaction with oxygen (expressed as gO₂/gcoal/s), A is a constant, f(r) is a function which depends on the coal particle size distribution, C is the oxygen concentration, n is an empirical exponent, E the apparent

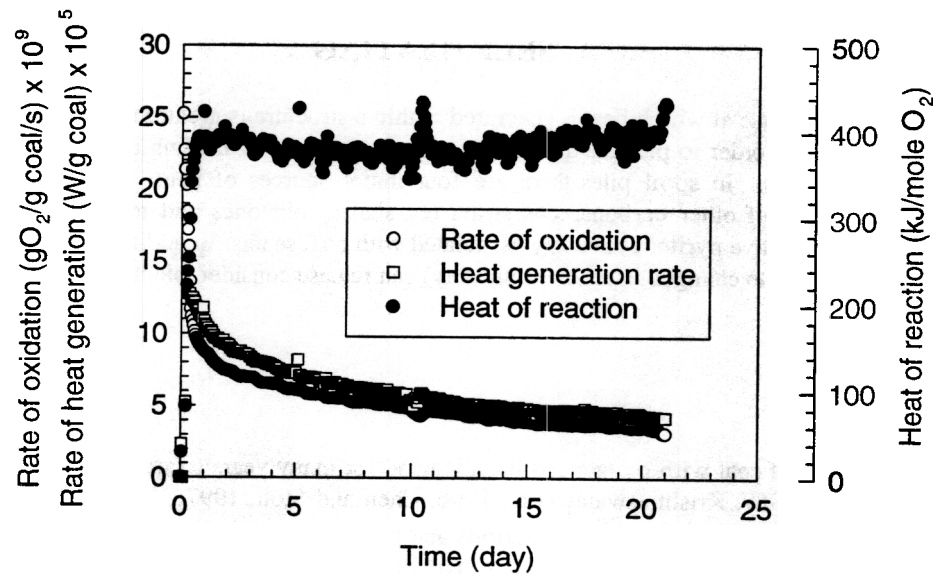


Fig. 2 - Rate of oxidation, rate of heat generation and heat of reaction for an Australian coal at 55°C

activation energy, R the gas constant, T the temperature, α an empirical factor and q the amount of oxygen that has reacted with the coal. In the above equation the first exponential describes the Arrhenius behaviour, the second the Elovich behaviour.

2. Carbonaceous material oxidation

The carbonaceous materials present in the spoil pile are generally less reactive than coal but there are normally vastly greater quantities of these materials than coal. Also, should combustion begin, these materials can provide a major fuel source for subsequent combustion as their specific energies can be very significant.

The oxidation rates of a variety of carbonaceous materials from open cut coal mines have been measured (Carras et al , 1994). The measurements show essentially the same features as coal oxidation, albeit at a reduced rate. Fig. 3 shows the rate of oxidation (determined at 14 days after the measurement began) for carbonaceous shales from some Hunter Valley mines.

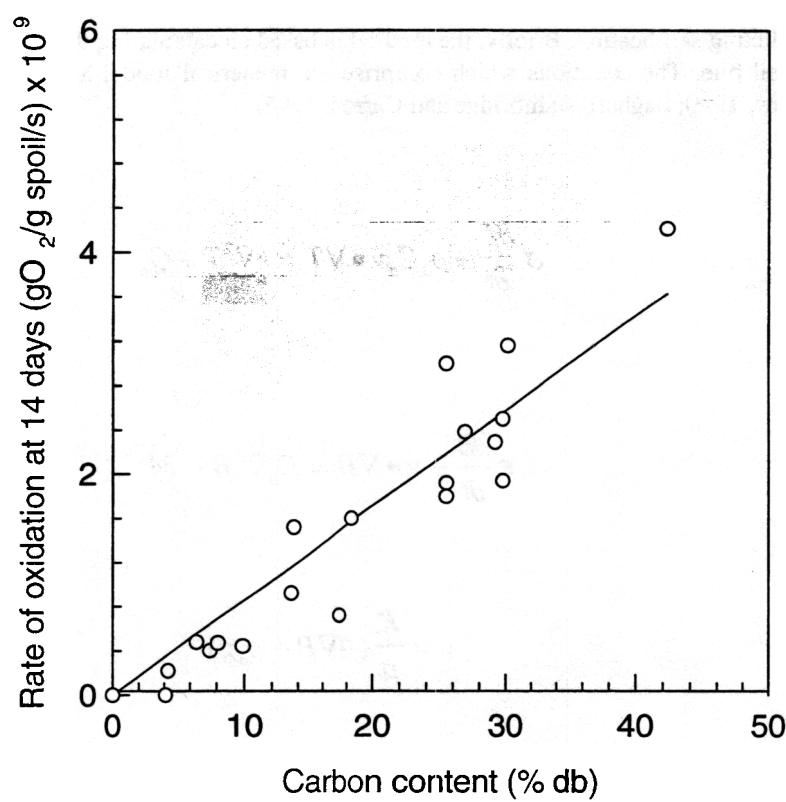


Fig. 3 - Rate of oxidation after 14 days for some Hunter Valley spoil vs carbon content (db)

The data include materials from both the Greta and Whittingham coal measures (Carras et al, 1994). The data in Fig. 3 show that the rate of reaction (and hence heat generation) is correlated well with the carbon content of the materials. The heat of reaction as determined by isothermal calorimetry has a range of ~290 to 360 kJ/mol O₂ which is similar to the range measured for coals. The rate of reaction of carbonaceous shales has been shown to be able to be described by a similar equation to the one used above for coal.

3. Pyrite oxidation

The third heat source in spoil piles is the oxidation of pyrite. There has been considerable work on pyrite oxidation, particularly as it affects acid generation (Harries and Ritchie, 1981 and Jaynes et al, 1983). In some spoil piles, pyrite oxidation may be a significant contributing factor to self heating and further work is required for the relative importance of pyrite, coal and carbonaceous materials in spoil piles to be quantified from their self heating perspective. In coal stockpiles it is usually unimportant.

4. Water Vapour

Water vapour can play two roles in the heat balance. Changes in ambient relative humidity can lead to the condensation of water vapour in the coal stack. This can liberate significant heat. Similarly the evaporation of water can result in significant heat loss. In addition other workers have suggested that water may play a significant chemical role in the oxidation processes (Chen and Stott, 1993).

PREDICTING SELF-HEATING

The rate of heat generation described above for coal and carbonaceous shales can be used as the basis for the development of a method for predicting self heating. Briefly, the method is based on calculating the relative rates of heat generation and dissipation for a spoil pile. The equations which comprise the numerical model are summarised below (Nordon, 1979; Glasser and Bradshaw, 1990; Saghafi, Bainbridge and Carras, 1995).

1.

$$\sigma \frac{\partial T}{\partial t} + \rho_a C_a v \cdot \nabla T = k \nabla^2 T + Q_o$$

2.

$$\varepsilon \frac{\partial B}{\partial t} + v \cdot \nabla B = D_b \nabla^2 B - M$$

3. Momentum

$$v = \frac{K}{\mu} (-\nabla P + \rho_a g)$$

4. Continuity

$$\nabla \cdot v = 0$$

In the above equations T is temperature, σ is the composite thermal capacity of the medium, k is the composite thermal conductivity of the medium, ρ_a , C_a are the density and heat capacity of air, v is the velocity of air, ε is the pile voidage, Q_o is the total rate of heat generation and includes the heat of water condensation or evaporation as well as oxidation, B the concentration of oxygen or water vapour in the voids, D_b the respective effective diffusion coefficient, M the rate of depletion of oxygen through reaction, or the rate of depletion or production of water vapour which may condense or evaporate, P is the air pressure, K the specific permeability, μ the dynamic viscosity of air and g the acceleration due to gravity.

In general the thermal conductivity depends on the materials, the packing of the spoil pile and the moisture content. The variation of gas density with temperature is only taken into account in the buoyancy term. The extent to which convection is important depends on the permeability of the spoil pile and on the external pressure distribution. In spoil piles it is the result of barometric pressure changes and the effect of winds. Numerical values for the permeability of spoil piles must at present be assumed.

Simplified versions of the general model outlined by the above equations have been applied to coal stockpiles, spoil piles and goafs. Spoil pile simulations to which the model has been applied include both drag line and truck tipping. The model for spoil allows for the influence of differing voidages through the depth of the pile as well as the presence of fractures which can act as conduits and provide access of oxygen deep within spoil piles (Carras et al 1994).

MODELLING SPOIL PILE SELF HEATING

In this section an example of the use of the CSIRO numerical model to predict spoil pile self heating is presented. Fig. 4 shows the spoil pile to be modelled.

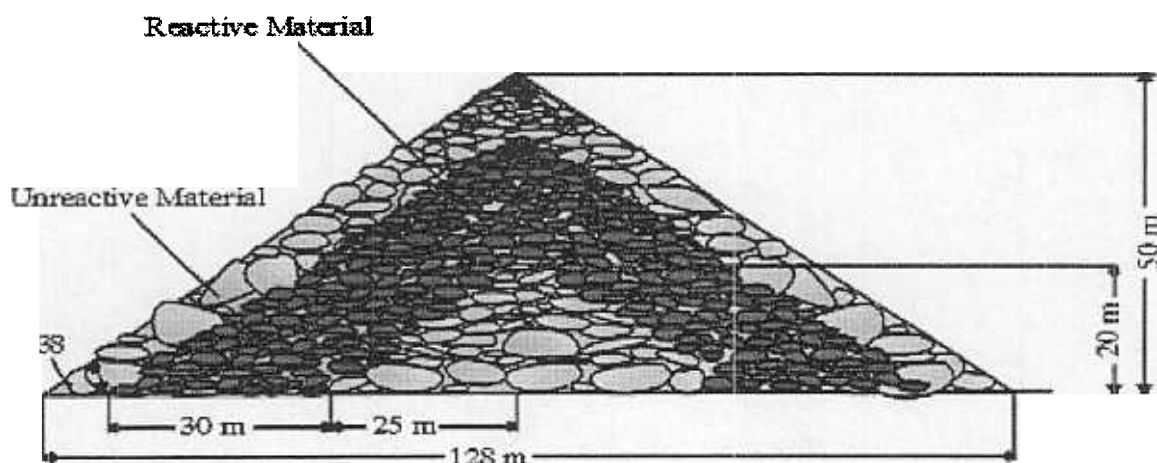


Fig. 4 - Section of the simulated spoil pile, reactive zone surrounded by unreactive materials

The reactive zone of carbonaceous material is assumed to have been excavated by the dragline and to have formed a symmetrical cone around the initial sandstone overburden. Further inert material has then been dumped over the reactive material. The purpose of this illustrative calculation is to show how the spoil pile heating characteristics depend on the reactivity of the reactive zone. From a practical perspective this region can be considered to be a zone where inert material and reactive coal are mixed due to the mining process.

The spoil pile modelled had a height of 50 m and a base width of 128 m. The reactive zone was considered to extend over a depth of 20 m. The above geometry and materials distributions were used as inputs to the CSIRO numerical model along with values for the reactivity of a Hunter Valley coal and other spoil pile characteristics measured on Hunter Valley spoil piles. The numerical model was used to simulate heating over a 6 month period.

Fig. 5 shows contours of temperature for the case of the zone being made up solely of coal. The temperature maximum ($T_m = 31\text{ }^{\circ}\text{C}$) is at the location where the coal can be accessed by oxygen from two sides. Similarly Fig. 6 shows the corresponding oxygen contours. Oxygen is rapidly depleted in the reactive zone.

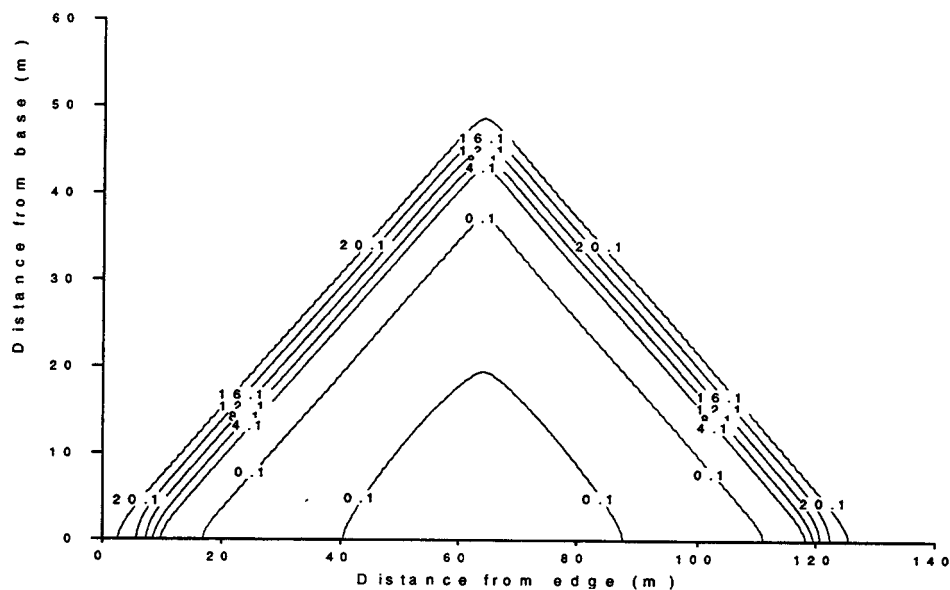
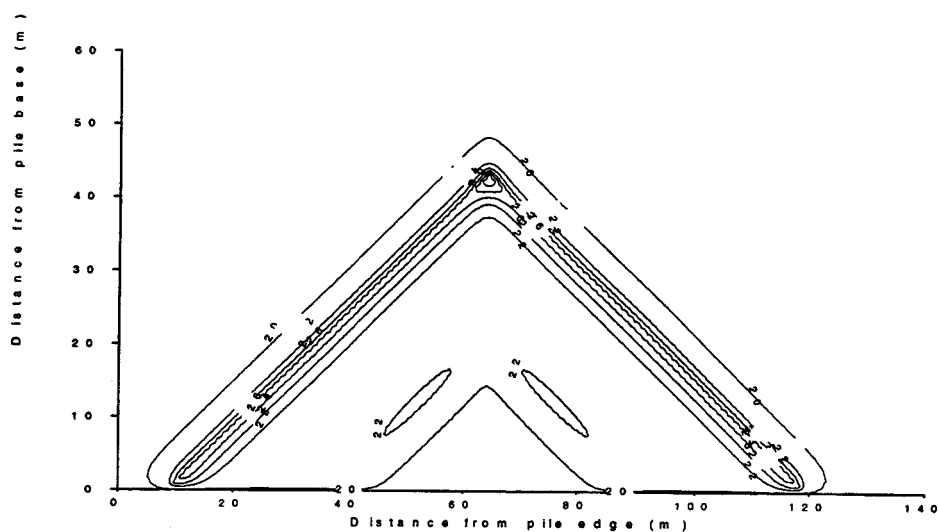


Fig. 7 shows the maximum temperature (after a simulation time of 6 months) as the proportion of coal in the reactive zone was varied from 0 to 100% coal.

While the above presentation showed the use of a numerical model to predict spontaneous combustion in spoil piles, methods to combat and control real self heatings are described in Carras et al, (1997) and Haneman and Roberts(1997) which the interested reader should consult for greater detail.

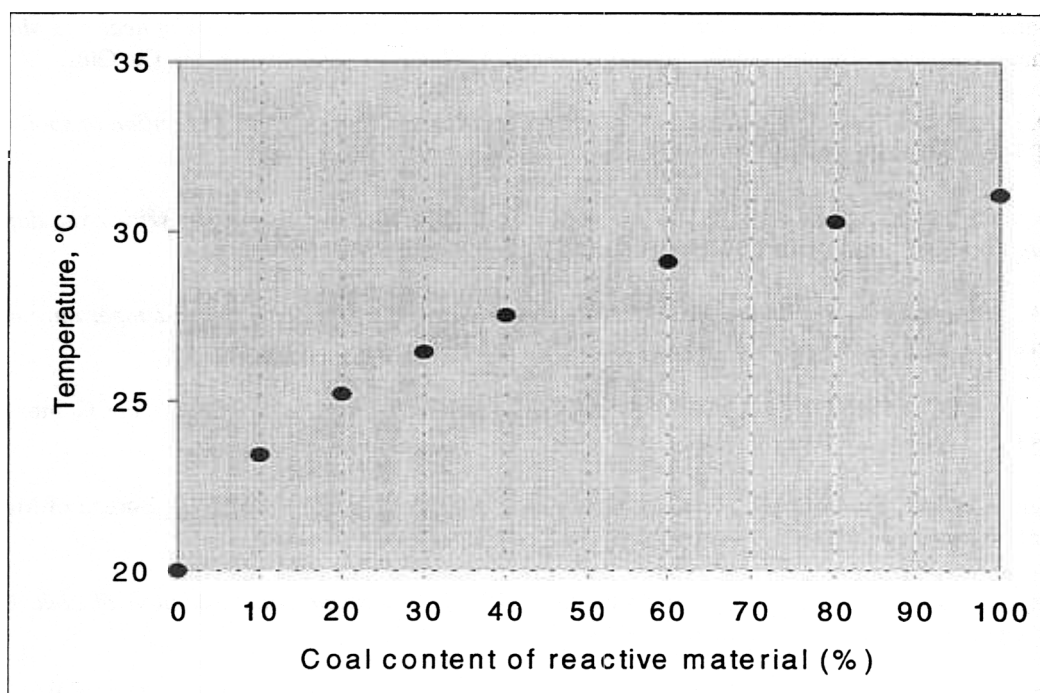


Fig. 7 - Maximum temperature in spoil pile vs carbon content of reactive waste

CONCLUSION

Self heating in spoil piles is due mainly to the interaction of coal and carbonaceous spoil materials with oxygen and water. Should the heating remain unchecked, spontaneous combustion can result with attendant safety, environmental and economic consequences. While considerable progress has been made in recent years on the understanding and modelling of spontaneous combustion the processes involved are sufficiently complex that greater work is required for methods to be developed which will allow accurate predictions of self heating and spontaneous combustion in spoil piles. It is hoped that the model presented will demonstrate what advances can be made in prediction of spontaneous combustion with presently available data.

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